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# Ohmic Contacts to Semiconducting Diamond

K. L. MOAZED, RICHARD NGUYEN, MEMBER, IEEE, AND JAMES R. ZEIDLER, SENIOR MEMBER, IEEE

**Abstract**—Natural semiconducting diamond samples (Class II-b) were used to develop techniques for the production of reproducible low-resistivity ohmic contacts for diamond devices. Annealed tantalum/gold and titanium-gold deposits on {100} polished diamond surfaces reduced the resistance by seven orders of magnitude relative to the as-received samples. The interfaces were characterized using metallography, scanning electron microscopy, and secondary ion mass spectrometry.

## I. INTRODUCTION

SEMICONDUCTING diamond exhibits a unique combination of electrical, optical, and physical properties, e.g., low thermal impedance, low dielectric constant, high strength, excellent corrosion resistance, high breakdown voltage, radiation hardness, high saturated carrier velocities at high electric fields, and optical transparency over a wide frequency range.

The growth of boron-doped diamond films, by plasma-assisted CVD, with an electrical resistivity in the range of  $0.001$ – $1 \Omega \cdot \text{cm}$  was reported to be monocrystalline when deposited on a diamond substrate and polycrystalline when deposited on a silicon substrate [1]. More recently, the first diamond transistor with power gain has been reported [2]. Electrical contacts to these devices were obtained using tungsten point contacts.

Metal contacts applied to the smooth surfaces of semiconducting diamonds have exhibited extremely large electrical impedance due to the large potential barrier of approximately  $4 \text{ eV}$  [3]. Although a variety of techniques have been used to obtain electrical contacts to natural and synthetic diamonds [3], [4], these techniques have not yet been evaluated to determine the most desirable approach for device fabrication. This letter reports on a solid-state reaction process for producing ohmic contacts to polished natural semiconducting diamond surfaces. The approach attempts to systematically characterize the processes which occur when metallic films of known thickness are deposited on a smooth diamond surface and annealed in the solid state under controlled conditions.

## II. RESULTS

The natural semiconducting diamond samples (Class II-b) used in this study were square plates with edge dimensions of  $5 \text{ mm}$  and a thickness of  $0.25 \text{ mm}$ . The crystallographic orientation of the faces was {100} and of the edges {110}. The current-potential ( $I$ - $V$ ) characteristics of the samples were

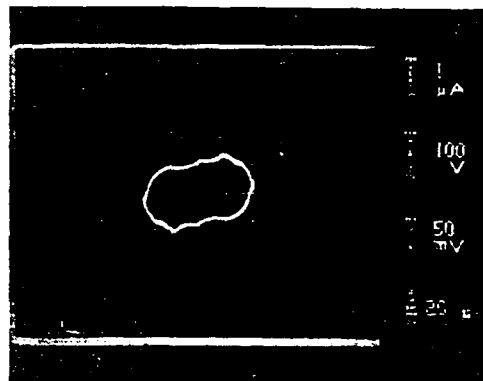


Fig. 1. Typical current-potential ( $I$ - $V$ ) characteristics of the as-received diamond samples for intermediate values of applied potential.

measured using a pair of sharp tungsten probes with a separation distance of  $\sim 0.5 \text{ mm}$ . An applied potential of  $10\text{-V}$  dc produced a current of less than  $0.1 \text{ pA}$ . The electrical response of the as-received samples to higher ac applied potentials, prior to reaching the "threshold" potential, was typified by the behavior which is illustrated in Fig. 1. The "threshold" potential varied from sample to sample in the range of  $300$ – $1000 \text{ V}$ . Once the "threshold" potential was reached, a current of  $\sim 10^{-5} \text{ A}$  flowed at potentials substantially less than the "threshold" potential. The response of a sample after a "threshold" potential of  $350\text{-V}$  ac was applied to it is seen in Fig. 2, where a current of  $\sim 2 \times 10^{-5} \text{ A}$  flows at a potential of  $150\text{-V}$  ac.

Each corner of a  $5 \times 5\text{-mm}^2$  face of a diamond sample was metallized sequentially with titanium and with gold and annealed to produce ohmic contacts, using procedures which will be described later. Wire leads were attached to the metallized corners for Hall effect measurements. The Hall mobility, carrier concentration, and resistivity measurements were made over the temperature range of  $170$ – $380 \text{ K}$  using the Van der Pauw technique. The carrier concentration varied from  $3 \times 10^{14} \text{ cm}^{-3}$  at  $380 \text{ K}$  to  $3 \times 10^{12} \text{ cm}^{-3}$  at  $170 \text{ K}$ , while the resistivity varied from  $9 \times 10^3$  to  $2 \times 10^6 \Omega \cdot \text{cm}$  in the same temperature interval. The carrier activation energy was  $0.32 \text{ eV}$  in the interval of  $277$  to  $380 \text{ K}$ , in agreement with published results for natural diamond [1].

Using photolithography and a Shockley pattern mask, a grid of metallic pads of known area and of known variable spacings was deposited on the diamond ( $\text{C}_1$ ) surface. A gold (Au) film,  $150 \text{ nm}$  thick, was sequentially deposited on top of a tantalum (Ta) film,  $10 \text{ nm}$  thick, in an ion-pumped ultra-high vacuum system using an electron-beam evaporation source. After the removal of the resist, a nonohmic current of  $\sim 1 \text{ pA}$  at a potential of  $10\text{-V}$  dc was measured.

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K. L. Moazed is with North Carolina State University, Raleigh, NC 27695. R. Nguyen and J. R. Zeidler are with the Naval Ocean Systems Center, San Diego, CA 92152.

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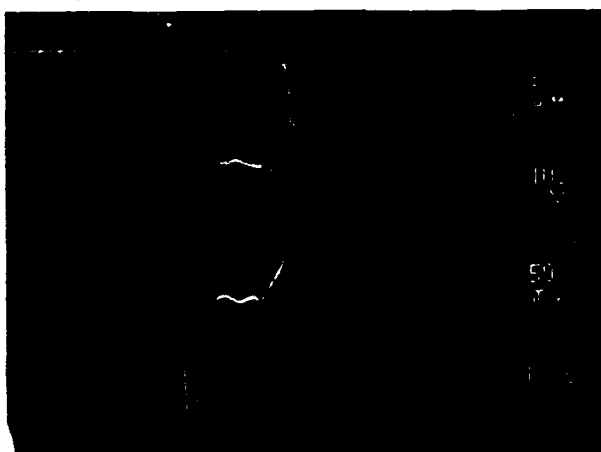


Fig. 2. Typical current-potential ( $I$ - $V$ ) characteristics of the as-received diamond samples subsequent to surmounting the "threshold" potential.

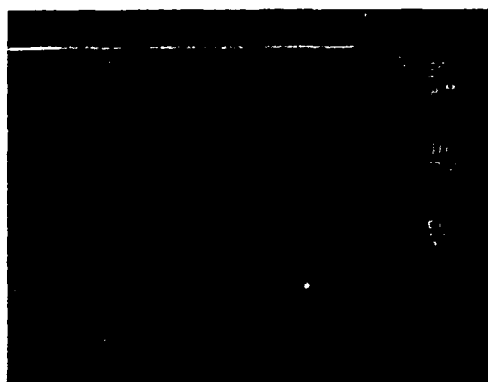


Fig. 3. Typical current-potential ( $I$ - $V$ ) characteristics of two adjacent rectangular pads (separation distance of 50  $\mu$ m) metallized with Ta/Au after 1 h of annealing at 885°C.

Next, the  $\langle C \rangle$ /Ta/Au sample was annealed for 1 h at 885°C in a quartz tube furnace in an atmosphere of flowing purified hydrogen gas. The annealed sample exhibited linear dependence of current to the applied potential (illustrated in Fig. 3). The annealing process had reduced the resistance from a value of  $\sim 10$  g $\Omega$  to a value of 3.5 k $\Omega$ , a reduction of approximately seven orders of magnitude.

Metallographic examination of the annealed sample revealed a significant reduction in the thickness of the gold deposit, by evaporation, during the annealing cycle. To prevent the possibility of short circuiting between pads by evaporation and recondensation during annealing, all subsequent samples were capped by a silicon nitride film (200–300 nm thick) prior to annealing. The silicon nitride layer was very effective in preventing the transportation of gold during annealing.

Metallographic and SEM examination of the  $\langle C \rangle$ /Ta/Au samples that were capped with silicon nitride and annealed revealed that the metallized regions had a microstructure of equi-axed grains with well-defined grain boundaries and a mosaic substructure, which typifies an annealed metallic microstructure. The electrical response of the sample which was capped during annealing was essentially the same as the

sample which had not been capped. Recapping and further annealing of the sample for an additional hour at 885°C produced no significant change in the electrical response of the sample. Consequently, one may postulate that the reaction of the thin film of tantalum with the diamond substrate had been completed within the first hour of anneal and that the reaction products remained stable during the subsequent hour of anneal.

A tantalum film, approximately 8 nm thick, was simultaneously deposited on a face of each of two diamond samples. One of the samples was retained in the as-deposited condition, while the other sample was capped and annealed for 1 h at 885°C. Secondary ion mass spectrometry (SIMS) was used to analyze the as-deposited sample and the annealed sample, after removing the silicon nitride cap. SIMS results indicated that shallow penetration of tantalum into the diamond substrate may have occurred during annealing.

A diamond sample that had been metallized with a 12-nm-thick titanium film, overlaid by a 170-nm-thick gold film, and capped and annealed for 1 h at 775°C (to prevent the high-temperature allotropic transformation) exhibited an electrical response similar to that obtained with  $\langle C \rangle$ /Ta/Au samples. An additional hour of annealing at the same temperature did not significantly change the electrical response of the  $\langle C \rangle$ /Ti/Au sample.

### III. CONCLUSIONS

This study demonstrates that carbide forming metal films, such as tantalum and titanium, will produce satisfactory ohmic contacts to semiconducting diamond by an annealing process conducted in the solid state.

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